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Project Systemic Risk: Application Examples of a Network Model

Christos Ellinas^{1, 2, *}, Neil Allan^{2, 3}, Anders Johansson¹

Abstract

Projects are increasingly perceived as complex systems, yet little work has been done in developing methodologies that are theoretically grounded on complex systems theory. In response, this article argues the practical utility of a recently introduced model that draws on notions from Network Science (NS) – a prominent domain in the study of complexity. Its utility is exemplified in the context of Project Management (PM), tackling two specific challenges: risk and conflict management. In the case of the former (risk), shifts in the susceptibility of a project to systemic risk (in the form of inter-linked failures) are identified. In the case of the latter (conflict), the effect of (sub) contractor activity – in terms of variance and activity pattern – to project systemic risk is assessed. To do so, numerical methods are developed and applied on an empirical dataset of widely-captured data (Gantt charts). In the context of the two challenges proposed, it is shown that: (a) the exposure of a project to systemic risk varies in a non-trivial manner as it evolves, at both micro and macro level; (b) (sub) contractor activity substantially impacts the emergence of locally important tasks (i.e. tasks able to disrupt the operation of a (sub) contractor). From a theoretical perspective, this work initiates a dialogue between the two domains (PM and NS), potentially opening new ways of tackling long-lasting challenges of PM.

Keywords: Project Management; Network Science; Systemic Risk; Conflict Management

1. Introduction

Coordination of human endeavour lies at the core of management science; project being invoked as the medium for the delivery of such endeavours. Managing their successful delivery is a daunting task, partly due to the multiplicity of risks that can manifest and subsequently affect project performance (PMI, 2008). Driven by the practical nature of the challenge, Project Management (PM) is a field dominated by professional associations (e.g. PMI, APM) striving to improve project performance (Geraldi et al., 2011). Through these associations, statements of best practice – in the form of endorsed Bodies of Knowledge (BoK) – are devised, promoted and subsequently practiced across the globe. As a result, the use of billions of USD worth of resources, and to an extent human prosperity, is highly dependent on the validity of the tools, methods and assumptions that underlie these BoK. Yet, modern projects appear to challenge

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this validity (Cooke-Davies et al., 2008; Geraldi et al., 2011; Marle et al., 2013; [Vidal and Marle, 2008](#); [Williams, 1999](#)), with improvements in project performance remaining illusive at best (at worst, resulting to a major failure – for examples see (Bar-Yam, 2003; Williams, 2002)).

Geraldi et al. (2011) have proposed that this evident mismatch between best practice and project success lies at an increasingly relevant aspect of modern projects – project complexity. Despite the young age of this notion (first suggested by Baccarini (1996)) its relevance has been increasingly recognized by both academia and industry – see (Bar-Yam, 2003; Cooke-Davies et al., 2008; Mele et al., 2010; Remington and Pollack, 2007; [Vidal and Marle, 2008](#); [Williams, 1999, 2002](#)) and (ICCPM, 2011; PMI, 2013) respectively. As a result, recent work has focused on exposing the nature of project complexity by identifying and subsequently mapping its components (Geraldi et al., 2011; [Vidal and Marle, 2008](#); [Williams, 2005](#); [Williams, 1999](#)). Such work opens new paths in tackling more practically-oriented challenges such as project complexity evaluation, along with assessing (and ultimately, controlling) the influence of complexity over project performance.

Similarly, recent work within the field of Network Science (NS) has concentrated on similar challenges (Liu et al., 2011), with a focus on understanding the impact of complexity (in the form of non-trivial features of the system (Barabási, 2007)) on the performance of various systems⁴ (abstracted as *networks*) (Albert and Barabási, 2002; Newman, 2003). Work around the dynamical processes that can undermine (or enhance) the operation of such systems has become increasingly relevant ([Vespignani, 2012](#)), with the case of failure cascades being at the forefront due to its evident practical implications (the economic crisis of 2007-2008 being a recent hallmark of its importance (Helbing, 2012)).

Such failure cascades (also known as “chain reaction”, “avalanches” or “dominos effects”) are the result of a cascading process and can substantially⁵ impact the performance of the entire system – the manifestation of such interlinked failures is the core definition of systemic risk (Helbing, 2013). In the context of risk management, such failures deviate from the traditional definition of risk, which is typically composed of two components: (a) the *independent* probability of a risk to materialise, and (b) its expected impact. However, quantifying (b) in a generic sense (and hence in step with the generic nature of these failure cascades) is fairly ambiguous due to its highly context-dependent nature. Hence studies on systemic risk typically focus on (a) i.e. the probability of systemic risk to materialise (Helbing, 2012;

⁴ A system is a general class of objects, which exists “in a given environment, aims at reaching some objectives (teleological aspect) by doing an activity (functional aspect) while its internal structure (ontological aspect) evolves through time (genetic aspect) without losing its own identity. Projects can thus be considered as systems.” Vidal, L.-A., Marle, F., 2008. Understanding project complexity: implications on project management. *Kybernetes* 37, 1094-1110.

⁵ Theoretically, this impact can be infinite; practically it is bound by the size of the system.

Namatame and Komatsu, 2011; [Tessone et al., 2013](#)). This is an increasingly challenging task due to its *interdependent* and the consequent need to account for non-trivial topological features that characterise these complex systems (Barabási, 2007).

Despite the clear relevance of the approach with concepts from PM (projects being referred to as complex systems e.g. (Cooke-Davies et al., 2008; [Vidal and Marle, 2008](#)); the use graph-theoretic concepts to reduce project risk e.g. ([Vanhoucke, 2013](#)) little work⁶ has been done to explore the capacity of projects to sustain systemic risk. In an attempt to trigger a dialogue between the two communities (PM and NS), recent work has proposed a model for simulating such failure cascades across projects, abstracted through their underlying activity network (Ellinas et al., 2015b) – herein we will refer to this model as the *cascade mode*. In this context, systemic risk can be interpreted as the consecutive failure of interlinked tasks that can result to a large portion of the entire project being affected.

However, Ellinas et al. (2015b) have emphasized the theoretical underpinning of the proposed model, leaving little space for an elaboration on its practical relevance. This may be interpreted as a serious obstacle for the PM community to actively engage, and consequently adopt, such approaches. In response, this work aims to fill this gap by: (a) briefly introduce the theoretical underpinning of the cascade model to a practically oriented community and (b) illustrate its practical utility through two application examples. By doing so, and in the spirit of (Anderson, 1999; Anderson et al., 1999; Borgatti and Foster, 2003), we hope to foster a dialogue between two seemingly unrelated fields – NS and PM. The academic contribution of this work is two-fold. Firstly, we illustrate the capacity of up-to-date project schedules in successfully capturing shifts in a project’s susceptibility to systemic risk. Secondly, we develop a modelling framework that utilises the cascade model to assess the emergence of locally important tasks (i.e. tasks capable of disrupting the operation of a given (sub) contractor). In particular, we examine the impact of variance in the number of involved (sub) contractors and their activity pattern in the context of conflict management.

The remaining article is structured as follows. An overview of the theoretical background and some practical challenges of PM will be presented in Section II. Section III will briefly introduce the empirical dataset and the core of the approach; results of the analysis will follow in Section IV. Section V will discuss the implications of this work, along with restrictions and potential avenues for further work. Section VI will conclude with a summarizing overview of the work. An Appendix is also included.

⁶ This is not to say that other subsets of management science have not benefitted from techniques borrowed from networks science – for a recent example see Hearnshaw, E.J., Wilson, M.M., 2013. A complex network approach to supply chain network theory. *International Journal of Operations & Production Management* 33, 442-469.; for an accumulation of work see Jackson, M.O., 2008. *Social and economic networks*. Princeton University Press Princeton., and references within.

2. Theoretical Background

2.1. Theoretical Underpinnings of Model

Several distinct methods have been proposed to better understand the emergence of systemic failures across complex systems, ranging from ordinary differential equations (Pastor-Satorras and Vespignani, 2001) and cellular automata (Bak et al., 1987) to agent-based (Rahmandad and Sterman, 2008) and threshold models (Goel et al., 2015). The proposed cascade model is part of the latter category (threshold models) and hence, a brief review of relevant literature follows. For the sake of completeness, the interested reader is referred to (Newman, 2011) for an overview of the remaining categories. Note that in the context of this work, a complex system is defined as a “system composed of many interacting parts, such that the collective behaviour of those parts together is more than the sum of their individual behaviours” (Newman, 2011). Of particular relevance to this work is the non-trivial nature of these interactions, as they tend to balance between order and randomness – a feature which in turn significantly affects the overall behaviour of these systems (Watts and Strogatz, 1998).

Threshold models have been used to understand a numerous phenomena that appear to emerge via a cascading processes, ranging from social unrest (Granovetter, 1978) and online virality (Goel et al., 2015) to disease epidemics (Watts, 2002) and financial contagion effects (Ellinas et al., 2015a). At the core of these approaches lies a threshold value, at which the behaviour of a node changes if a given threshold is exceeded. Clearly, this threshold value must reflect some contextual aspect by which the operation of each node (and collectively, the entire network) operates. However, increased contextualisation during the model formulation sacrifices the generalizability of the insight produced (a necessary ingredient for theory building) for the sake of increased contextual relevance (which benefits operationalization) (Willinger et al., 2002). The majority of approaches that use the threshold model adopt the former approach (generalizability) by defining the threshold value in an absolute way, either using arbitrary values (e.g. (Watts, 2002)) or empirical estimates (e.g. (Battiston et al., 2012)). Seminal work by Lorenz et al. (2009) epitomizes this vision, suggesting that threshold models can serve as a unifying framework for understanding a wide spectrum of phenomena, regardless of the context of the system. Such views are dominant within the natural sciences and has yielded several powerful insights on global properties of the systems that can sustain these collective phenomena (Lorenz et al., 2009; Vespignani, 2012). However, contextual abstraction and a focus on the global level of the system have raised concerns in terms of the practical utility of such models, in terms of supporting the decision making process (Borgatti et al., 2009; Willinger et al., 2002). In other words, absence of contextual information in the core mechanics of the model (such as the use of absolute, and often arbitrary, values in the threshold value; lack of contextual

information⁷) and a lack of focus on the local level of the system (where decision making is most often executed) challenge the practical utility of such models.

In response, recent work has proposed a number of amendments in order to support the risk management function of PM, with respect to project systemic risks (Ellinas et al., 2015b). These key changes captured by the proposed cascade model are as follows: (a) a shift from an absolute to a *relative* threshold, in order to account for the increased variance of all possible tasks that may be included in a project, (b) quality of completion as a function of a specified resource introduces an important contextual aspect to the mechanics of the model and (c) there is an explicit focus on the local level of the of the project, enabling decision makers to quantify the impact of individual tasks failing.

2.2. Application Examples' Premise

Two operational challenges of the project risk management function will provide the context upon which the applicability and utility of the cascade model will be exemplified: (a) assess the change in the exposure of a project to systemic risk as the project evolves during its lifecycle, and (b) evaluate the capacity of a project to promote conflict between the involved (sub) contractors. Point (a) has direct implications on the framework set to monitor the risk levels of the project during its delivery, while (b) has direct implications over the procurement strategy.

2.2.1. Temporal Monitoring for Project Systemic Risk

Unsuccessful management of project evolution is a significant aspect of project failure, typically triggered through changes in the project schedule (Assaf and Al-Hejji, 2006; Pinto and Mantel Jr, 1990), accumulated through changes in the scope of a project and/or the emergence of mitigation tasks introduced to account for unforeseen events (e.g. risk manifestation).

As a result of changes in the project schedule, a shift to the critical path⁸ (and consequently, the critical tasks) may be triggered, suggesting that temporal monitoring of the state of the project is an important aspect of the risk management function. Current approaches rely on keeping an up-to-date project schedule and subsequently tracking changes in task criticality in order to manage the impact on a variety of project risks e.g. delay in delivery (PMI, 2008). Within this work, the cascade model will be used to

⁷ Interestingly, this limitation appears to extent to even in context-specific methodologies, where contextual information is often ignored during the decision making process – for a case of the project risk management domain see Fan, M., Lin, N.-P., Sheu, C., 2008. Choosing a project risk-handling strategy: An analytical model. *International Journal of Production Economics* 112, 700-713.

⁸ A sequence of tasks that adds up to the longest duration, and consequently determines the shortest possible time to complete a project. Hence, a delay of x days in delivering a task that lies on the critical path will result to a delay of x days to the overall project, making the task to be critical.

extend this approach to project systemic risk. By doing so, the dynamic character of tasks capable of triggering large failure cascades will also be illustrated.

For the reader's reference, we note that project systemic risk is defined as the risk of having a number of tasks failing due to their interdependent nature. As such, project systemic risk can be quantified by enumerating the number of tasks affected by the failure of a single task, captured by the size of the resulting failure cascade.

2.2.2. *Conflict Management*

Conflict between the involved (sub) contractors (and often, the project owner(s)) is a frequently cited phenomenon across the construction industry – see (Harmon, 2003) and references therein. Legally binding agreements are consequently put in place in order to protect the involved parties whilst providing dispute resolution mechanisms. Importantly, the procurement strategy which underlies these contracts can itself poses a significant risk, as it can significantly affect the possibility for conflict risk to emerge (Assaf and Al-Hejji, 2006; Gardiner and Simmons, 1992), eventually leading to poor project performance (Odeh and Battaineh, 2002).

In recognition of this challenge, the UK government has actively been promoting increasingly collaborative forms of procurement⁹ over traditional procurement methods (where the contract is awarded to the lower bidder). Nonetheless, these traditional procurement methods are still largely dominating the UK construction industry (National Building Association, 2013). Part of the challenge in using traditional procurement strategies is the adversarial conditions that they foster, by promoting the involved parties to pursue their self-interest rather than mutual benefit (Akintan and Morledge, 2013; [Xue et al., 2007](#)).

In the context of project systemic risk, this self-interest can be understood in terms of task ownership i.e. every (sub) contractor is responsible for a number of tasks that he/she has agreed to deliver. Driven by self-interest, each (sub) contractor is expected to evaluate the criticality of each task based on how many other tasks that he/she owns can be subsequently affected by its failure. In contrast, the main contractor and/or owner will evaluate the criticality of each task based on its capacity to affect the *entire* project (i.e. the entirety of tasks). As such, grounds for conflict are bound to emerge if tasks that matter greatly to the main contractor and/or owner (i.e. have high global importance) do not attract the same interest by other sub-contractors (i.e. have low local importance). Within this work, we will illustrate how this capacity can be quantitatively assessed. We further illustrate the impact of (sub) contractor activity to the frequency of having tasks with a given capacity to disrupt their operations.

⁹ Both national and local government bodies in the UK mandate the use of NEC3 – a contractual suite focusing on promoting collaboration through the introduction of various mechanisms.

3. Methodology

3.1. Data

Projects are multifaceted endeavours, spread across several dimensions which subsequently affect the overall complexity of a project e.g. organizational, technological etc. The focus of this work is on the latter (technological), defined as “the transformation process which convert[s] inputs into outputs” (Baccarini, 1996). This process is suitably captured by a project schedule, where dependencies between tasks are noted, along with temporal restrictions (i.e. task duration, start and end date). In additions, projects schedules form the main tool project risk management in practice ([Zwikael and Ahn, 2011](#)). Hence, the use of project schedules in assessing project systemic risk is both theoretically grounded and practically relevant.

Engineering projects with a focus on technical activities form the majority of modern organization activity ([Shenhar, 2001](#)), of which construction projects are a typical example. Furthermore, construction projects are frequently considered by practitioners as one of the more risky forms of projects ([Zwikael and Ahn, 2011](#)) and hence, form a suitable context. As such, a set of nine project schedules of a construction project¹⁰ is used. Each snapshot represents the up-to-date project schedule, which captured the state of the project at the specified point in time (Table I, Column 3). As such, it captures the evolving character of the project by highlighting changes in the number of tasks and links included in the schedule, along with shifts in the estimated project duration.

For each case, the project schedule was converted to a directed, activity-on-node (AON) network ([Węglarz et al., 2011](#)) $G = \{\{N\} \{E\}\}$, where every task i is abstracted as node i , $i \in N$ and a functional dependency between task i and j corresponds to a directed link (or edge) $e_{i,j}$, where $e_{i,j} \in E$. The overall structure of the network can be subsequently stored in a matrix form using the adjacency matrix \mathbf{A} , where $\mathbf{A}(i,j) = 1$ when there is a link between node i and j , and 0 otherwise. Relevant details of the project schedule and AON network are shown in Table I, column 2-4 and column 5-6 respectively.

¹⁰ Due to confidentiality issues, the details on the nature of the project remain undisclosed. Nonetheless, our ability to analyse the project remains intact due the availability of the project schedules.

Table I: Dataset Used

| Case | Project Date | Start | Last modified on (days from project start) | Expected Duration (days) | Node Count | Edge Count |
|------|--------------|-------|--|--------------------------|------------|------------|
| 1 | 04/12/2004 | | 17/01/2005 (+45) | 418 | 775 | 822 |
| 2 | 04/12/2004 | | 14/02/2005 (+73) | 404 | 801 | 852 |
| 3 | 04/12/2004 | | 07/03/2005 (+94) | 404 | 823 | 876 |
| 4 | 04/12/2004 | | 28/03/2005 (+115) | 404 | 822 | 875 |
| 5 | 04/12/2004 | | 12/04/2005 (+130) | 404 | 823 | 872 |
| 6 | 04/12/2004 | | 26/04/2005 (+144) | 404 | 823 | 872 |
| 7 | 04/12/2004 | | 23/05/2005 (+171) | 418 | 822 | 867 |
| 8 | 04/12/2004 | | 30/05/2005 (+178) | 383 | 821 | 866 |
| 9 | 04/12/2004 | | 24/06/2005 (+203) | 409 | 828 | 856 |

3.2. Method

The core dynamics of the cascade model are presented within this section, with further supporting information found in the Appendix. It should be noted that an extensive elaboration of the theoretical underpinnings of the dynamics is beyond the scope of this work – the interested reader is referred to (Ellinas et al., 2015b). Finally, it is noted that a 10 independent runs were performed for each parameter tested, with $\sigma \in [1,4]$ in increments of 1, and $w \in [0,40]$ in increments of 5.

3.2.1 Nodal Definitions

With a focus on the local level, every individual node is assigned both intrinsic and extrinsic characteristics that described a number of properties. Specifically, intrinsic properties refer to aspects that a node, has irrespective of its interactions with other nodes, while extrinsic aspects emerge precisely due to this interactions. As such, intrinsic and extrinsic properties are explicitly decoupled from one another.

In the case of the former, (intrinsic) a node is described by its quality of completion (q_j), which is a function of resource spent. In this context, the term “resource” corresponds to the amount of time allowed for the delivery of a given task according to the project’s schedule, measured in days. Due to its wide adoption within the domain, the form of the function is sigmoidal, though various other forms can also be considered (e.g. linear and exponential) – see Section 1, Appendix for the formal definition.

Extrinsic characteristics have been used to describe two specific aspects that arise through the interdependent nature of the nodes – the capacity of a node to affect other nodes (its spreading power, \mathcal{C}_i^{SP}) and its capacity to be affected by other nodes (its sensitivity, \mathcal{C}_j^S). Importantly, \mathcal{C}_i^{SP} and \mathcal{C}_j^S account

for both structural and temporal complexity aspects of the project using graph-theoretic measures into their definition – for formal definitions see Section 2, Appendix.

Subsequently, the threshold condition is specified as follows:

$$c_j^S + c_i^{SP} \geq \frac{\alpha}{100} \times q_j \quad (\text{eq.1})$$

where the use of q_j indicates that a task with a higher quality of completion is increasingly robust against failure, and α serves as a scaling factor for the threshold, which is externally varied, $\alpha \in [0,200]$. In effect, by introducing variable α we are able to control the efficiency at which each task utilizes its assigned resource to deliver a given level of quality. As such, three distinct scenarios can be formulated: (a) when $\alpha = 0$ no threshold is provided and hence, the maximum failure cascade triggered by each node is obtained; (b) when $\alpha = 100$, resources are roughly¹¹ assigned as planned and (c) when $\alpha = 200$, extra resources are individually assigned to each task in order to resist failure.

3.2.2. Model Dynamics

Due to the recursive form of the model, an algorithmic description is best fitted to describe the dynamics of the cascade model. Specifically, Step 1 specifies the parameters that are to be used in terms of resource efficiency (α) along with the quality function used – this intrinsic attribute is subsequently assigned in Step 2b. Step 3 recursively repeats the process by using the condition set in eq. 1 to all neighbouring nodes of i until no change is experienced in terms of their state (i.e. no node fails), with Step 4 capturing the total number of nodes that have been affected by the failure of node i . This process is then repeated for all nodes, as Step 1c suggests. The pseudo-algorithm is as follows:

Step 1: Model parameterization

- 1a: Set model parameter: $\alpha, \alpha \in [1, 200]$
- 1b: Define a quality function: Sigmoidal form.
- 1c: Define which node is artificially failed at the start of the simulation: k

Step 2: Model initialization

- 2a: Draw task fluctuations β_i^{pdf} from a statistical distribution.
- 2b: Set $q_i = f \left[\left(T_i^{\text{plan}} + \beta_i^{\text{pdf}} \right) / \left(T_i^{\text{plan}} \right) \right]$ for all i (eq. 1SI)
- 2c: Define initial node states at time $t=0$:

$$s_i(0) = \begin{cases} 1, & \text{if } i == k \\ 0, & \text{otherwise} \end{cases}$$

¹¹ “Roughly” as there is always a noise element added to simulate the stochasticity of the environment in which the project takes place in – see Section 3.2.2, step 2b.

Step 3: Model dynamics:

3a: Iterate simulated time $t = 1, 2, \dots$, until no more change happens:

- For all ‘affected’ nodes i (i.e. nodes where $s_i = 1$):
- For all successor nodes j of node i :

$$s_j(t) = \begin{cases} 1, & \text{if } \mathcal{C}'_j^S + \mathcal{C}'_i^{SP} \geq \frac{\alpha}{100} \times q_j \\ s_j(t-1), & \text{otherwise} \end{cases} \quad (\text{eq.2})$$

where s_j is the state of node j , $s_j \in [0,1]$ where $s_j = 0$ corresponds to non-affected and $s_j = 1$ to affected, t refers to simulation steps.

Step 4: Model outcome

4a: The number of affected nodes: $\sum_{j=1}^n s_j$

As such, the global importance of node i at a given α level (GI_i^α) can be quantified by the overall number of tasks that it can affect through its own failure – mathematically defined as:

$$GI_i^\alpha = \frac{1}{n} \sum_{j=1}^n s_j, \quad GI_i^\alpha \in [0,1] \quad (\text{eq.3})$$

3.3. (Sub) Contractor Assignment

Every involved (sub) contractor m is responsible for delivering a number of tasks, sc_m , where $m = 1, 2, 3, \dots, \beta$. We will refer to this aspect as the variance in the number of involved (sub) contractors. Furthermore, the activity of each (sub) contractor can follow various levels of involvement, ranging from delivering a consecutive number of tasks and then depart from the project, up to delivering a few tasks at regular intervals across the entire span of the project. We will refer to this aspect as the mixing pattern of (sub) contractor involvement, which can vary from a clustered scenario (consecutive tasks are delivered by the same (sub) contractor) to a well-mixed scenario (each (sub) contractor delivers a few tasks at regular intervals) – see Figure 1 for a simple example.

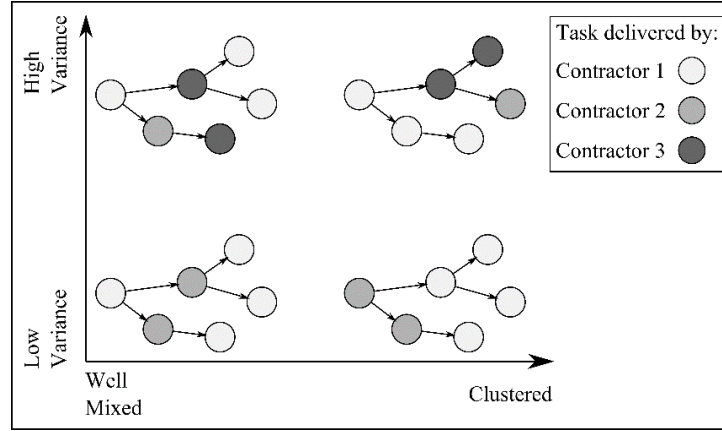


Figure 1: The impact of two aspects of (sub) contractor involvement in the delivery of a project – the variance in the number of (sub) contractors involved (y-axis) and the mixing pattern of their involvement (x-axis).

3.3.1. Contractor Variance

For each task, a random assignment is made in terms of the (sub) contractor responsible for its delivery¹². To do so, a random number, which corresponds to the (sub) contractor ID, is drawn from a suitably parameterized probability density function (pdf) and subsequently assigned to task i , with the process being repeated for all tasks. For the purpose of this analysis, a truncated Normal pdf was used, noted as $N(\alpha, \beta, \mu, \sigma)$ where α and β set the lower and upper limit, μ corresponds to the mean value and σ corresponds to the standard deviation. The use of a truncated Normal pdf satisfies two important conditions: (a) it can be bound (giving the ability to restrict the emergence of negative values, while setting a limit on the maximum number of contractors that will be considered) and (b) decays in an exponential manner. The second condition reflects the assumption that most tasks are performed by a small number of contractors. By keeping α , β and μ constant ($\alpha = 1$; $\beta = 15$; $\mu = 1$) and varying σ , a number of distinct variants have been tested: $N(1, 15, 1, 1)$; $N(1, 15, 1, 2)$; $N(1, 15, 1, 3)$ and $N(1, 15, 1, 4)$ – the number of tasks delivered by each (sub) contractor for each variant is shown in Figure 2.

¹² It is worth noting that in an operational context, this information is bound to be known.

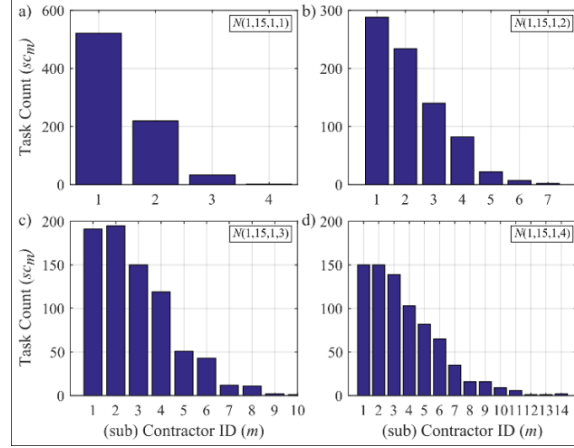


Figure 2: Typical breakdown of task ownership for each subcontractor (x-axis), as the standard deviation of the truncated Normal distribution varies from 1 to 4 (clockwise, subplot a-b respectively).

3.3.2. Contractor Mixing Pattern

The probability by which the same contractor delivers two consecutive tasks will be used as a control parameter to construct a range of mixing pattern scenarios, ranging from well-mixed to highly clustered instances (see Figure 1; x-axis). To do so, the probability P of (sub) contractor m to deliver the first task is defined by the proportion of tasks that it delivers:

$$P(\text{task } 1 \in sc_m) = \frac{|sc_m|}{n} \quad (\text{eq.4})$$

Once the (sub) contractor that delivers the first task is set, the probability that the subsequent task j is being delivered by (sub) contractor m is defined as:

$$P(\text{task } j \in sc_m) \sim \left(\frac{|sc_m|}{\beta} \right)^w, j \neq 1 \text{ and } \mathbf{A}(1, j) = 1 \quad (\text{eq.5})$$

where the operator “ \sim ” represents a proportional relationship, and the process is iterated across all tasks. As a result, the probability of the subsequent task (e.g. task 2) being delivered by the same contractor can be varied. In the case of $w = 0$, each (sub) contractor has a probability of 1 to deliver the subsequent task, and in effect results to an approximately¹³ well-mixed scenario where each (sub) contractor is equally likely to deliver each task. For larger values of w , this uniformity is destroyed and increasingly clustered scenarios are obtained. As an example, consider Figure 3 where $n = 775$ and (sub) contractor assignment

¹³ To be truly well-mixed, the pdf used for assigning (sub) contractors should be uniform, for each (sub) contractor to contribute a (roughly) equal number of tasks. As this is not the case (due to the Normal pdf used to assign tasks) (sub) contractors with fewer tasks are less likely to be involved as the index of the task increases as their pool of tasks runs out much faster than the (sub) contractors responsible of delivering the bulk of tasks. As a result, a decreasing trend is noted in Figure 3a. Despite this effect, (sub) contractor involvement can still be considered well-mixed in terms of the (sub) contractors that have yet tasks to deliver.

$\sim N(1,15,1,4)$. In the case of $w = 0$ a well-mixed case is obtained (Figure 3a), evident by the continuous fluctuations, with increased clustering being evident by the increasing smoothening of the involved (sub) contractor ID (Figure 3b-d).

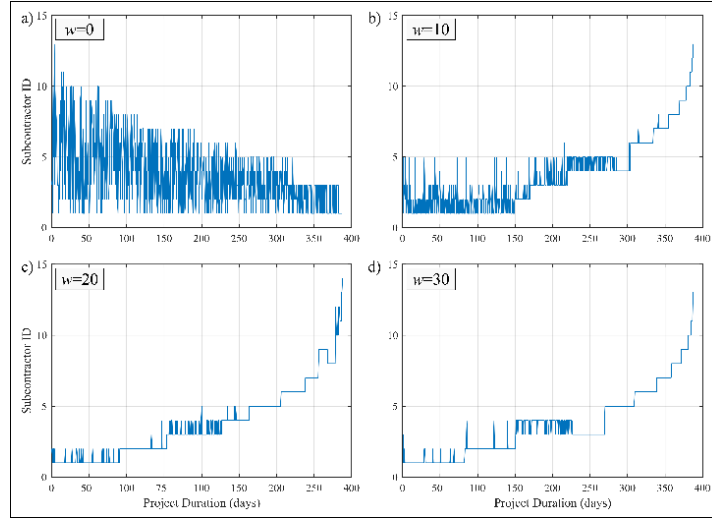


Figure 3: Typical example of a range of mixing patterns achieved by varying w (see eq. 5). Going from (a) to (d) clockwise, an increasingly clustered mixing patterns is evident by the smoothened involvement of (sub) contractors (y-axis).

The involvement of (sub) contractors necessitates the introduction of a new metric in order to capture the notion of task importance, as GI_i^α does not differentiate between varying (sub) contractors. In response, local importance (LI_i^α) is introduced, quantifying the number of tasks node i can affect, at a given α level, of which they share the same (sub) contractor:

$$LI_i^\alpha = \frac{1}{|sc_m|} \sum_{j=1, j \in sc_m}^n s_j, LI_i^\alpha \in [0,1] \quad (\text{eq.6})$$

where sc_m is a set containing nodes that are being delivered by contractor m . Such formulation adequately accounts for the variance aspect that describes (sub) contractor involvement, yet fails to capture the impact of varying the mixing pattern. To highlight this, consider the simple example presented in Figure 4. According to eq. 6, the local importance of node i is identical under both (a) and (b) – with $LI_i^\alpha = 0.6$. However, one would expect task i to be increasingly importance in case (b), as the contractor responsible for it is implicitly invested in the project for a longer period of time. Conversely, the local importance of task j is equal at both cases as its failure affects one more task (task k) and would necessitate the involvement of the responsible (sub) contractor an identical amount of time.

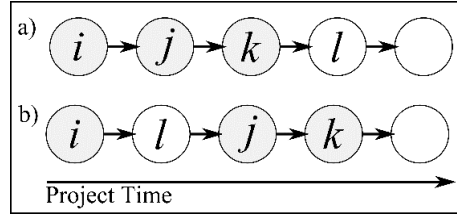


Figure 4: Trivial example illustrating the impact of mixing patterns in (sub) contractor activity, where case (a) corresponds to an increasingly clustered scenario, compared to case (b). Colours correspond to distinct (sub) contractors.

To account for the mixing patterns of activities, the factor $\varepsilon_{i,j}$ is introduced, capturing the time in which a given (sub) contractor is involved in the project, with respect to the entire project duration. This updated definition (\widehat{LI}_i^α) is defined as:

$$\widehat{LI}_i^\alpha = \varepsilon_i^\alpha \times \left(\frac{1}{|sc_m|} \sum_{j=1, j \in sc_m}^n s_j \right), \widehat{LI}_i^\alpha \in [0,1] \quad (\text{eq.7})$$

$$\varepsilon_i^\alpha = \frac{\max(t_j^{\text{end}}) - t_i^{\text{start}}}{t_n^{\text{end}} - t_1^{\text{start}}}, \varepsilon_i^\alpha \in [0,1] \quad (\text{eq.8})$$

where t_i^{start} and t_j^{end} represent the start date of task i and end date of task j respectively. Similarly, t_1^{start} and t_n^{end} representing the start date of the first task (i.e. the beginning of the project) and the end date of the last task (i.e. the end of the project), with their difference resulting to the overall task duration. The max function is used to identify the task scheduled the furthest from i , with $\max(t_j^{\text{end}}) - t_i^{\text{start}}$ capturing the time in which (sub) contractor m will have his/her attention focused on the project. As a result, local importance becomes a function of both the number of tasks that can be affected by task i and the time in which (sub) contractor m is actively engaged in the project.

4. Results

For the first example (Temporal Monitoring for Project Systemic Risk), each temporal snapshot of the project is analysed in terms of its susceptibility of failure cascades. A supplementary analysis on the project's sensitivity to resource perturbations is also performed. Both aspects can support the risk management function of PM. For the second example (Conflict Management) the model is used to highlight the potential disparity between global and local importance in terms of task criticality. By

further examining the impact of (sub) contractor variance and mixing patterns in their activity, their role in varying local importance of tasks is uncovered. Both aspects can support the procurement aspect of PM.

4.1. Risk management

Each snapshot of the project, captured by each Case in Table I, is assumed to adequately capture the state of the project at a given point in its development (Table I, Column 3). In doing so, two levels of analysis are proposed. At the macro level, changes in the susceptibility of the project to sustain failure cascades can be assessed, along with shifts in its sensitivity to resource perturbations. At a micro level, the criticality of individual tasks can be assessed, enabling educated resource assignment, reflecting changes in the activity network.

4.1.1. Macro

Consider the case where resources are delivered roughly as planned ($\alpha = 100$ in eq. 1), with Figure 5 presenting the cumulative probability plot for cascade sizes of a given size (for the sake of clarity, the plot is limited to Case 1 and 9). In terms of the largest possible cascade size, Case 1 scores the highest value, where roughly 6.20% of all tasks can be affected by a single failure cascade; Case 9 is increasingly more robust where roughly 5.07% of all tasks can be affected. In other words, the latest snapshot indicates that the project has improved in terms of its robustness against failure cascades, in the terms of the maximum possible failure cascades. A similar behaviour is exhibited in terms of global statistics of each Case, with Case 9 having the lowest mean and variance across all cascade sizes (Section 3, Appendix).

Interestingly, extend upon which Case 9 and Case 1 depends on the size of the failure cascade size considered. Specifically, a transition point is noted when failure cascades affect roughly more than 1% of all nodes – beyond this point the Case 9 is increasingly robust when compared to Case 1. As an example consider the probability of sustaining a failure cascade affecting up to 2% of all task, being 0.024 and 0.0085 for Case 1 and Case 9 respectively (relative difference of 182.35%). In the case of smaller failure cascades (i.e. affecting less than 1% of the total number of nodes), the probability of occurrence is much closer. As an example, the probability of sustaining a failure affecting up to 0.2% is 0.466 and 0.443 for Case 1 and Case 9 respectively (relative difference of 5.19%).

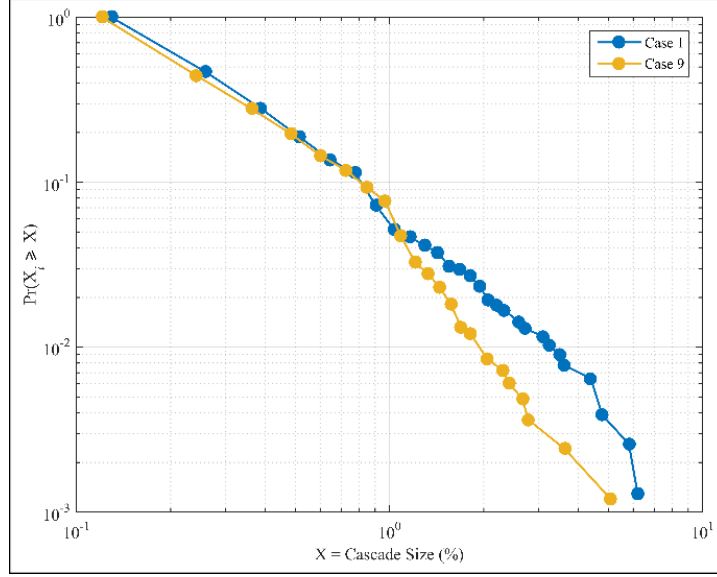


Figure 5: Cumulative Probability Distribution plot where the probability (y-axis) for a failure that affects at least X percentage of nodes (x-axis) is given for Case 1 (blue) and Case 9 (yellow). Note the double logarithmic axes used.

Shifting the focus to sensitivity to resource perturbations, Figure 6 presents the maximum portion of tasks that can be affected by a failure cascade across the entire spectrum of α , for Case 1 and 9. In terms of overall behaviour, both Cases show a qualitatively similar behaviour, with a monotonically decreasing fraction of tasks being affected as α increases, which is discontinuous at times (for $0 < \alpha \leq 86$), continuous for the subsequent interval (for $87 < \alpha < \sim 100$) and constant for the majority of remaining α intervals.

Despite their qualitative similarities, notable quantitative differences appear. Firstly, Case 1 can sustain larger failure cascades at low resource efficiency levels (up to $\alpha = 36$), with Case 9 becoming increasingly susceptible in the interval between $60 \leq \alpha < 82$. As a result, it is clear that Case 1 is more sensitive to changing resource efficiency (i.e. altering α) when compared to Case 9. In other words, Case 9 illustrates an increasingly robust behaviour when compared to Case 1 as its behaviour is less affected by changes in resource efficiency.

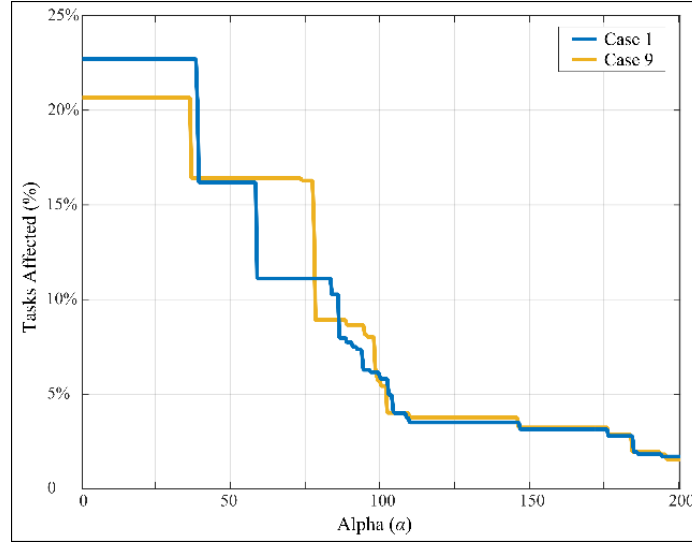


Figure 6: Size of maximum failure cascade size (y-axis) for Case 1 (blue) and Case 9 (yellow) across the entire range of resource efficiency (α ; x-axis). Case 1 shows an increased sensitivity to changing conditions, compared to Case 9, evident by an increased rate of change as α increases.

4.1.2. Micro

The cascade model allows for a detailed examination of tasks, in terms of their capacity to trigger¹⁴ large failure cascades. Consider Table II, where the five most influential tasks for each Case are presented, along with the damage that they can inflict. Generally, task criticality changes as the project evolves – as a result, the identity of critical tasks, along with their impact, follows suit. For example, Task 1 is consistently ranked as the most influential task, yet its actual impact monotonically decreases from 6.19% to 5.07%. Conversely, the identity of the 5th most influential task alternates between 5 different tasks – Task 3, 5, 7, 9 and 10 – with the actual impact also fluctuating.

Table II: Five most critical tasks (and their impact, as a proportion of all tasks) across all cases. Notice that some tasks are consistently ranked as high impact whilst others alternate.

| Case | 1 st (Impact) | 2 nd (Impact) | 3 rd (Impact) | 4 th (Impact) | 5 th (Impact) |
|--------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| Case 1 | Task 1 (6.19%) | Task 2 (5.81%) | Task 3 (4.77%) | Task 4 (4.39%) | Task 5 (4.39%) |
| Case 2 | Task 2 (5.99%) | Task 1 (4.37%) | Task 6 (3.00%) | Task 7 (2.75%) | Task 3 (2.75%) |
| Case 3 | Task 1 (5.23%) | Task 2 (4.01%) | Task 6 (3.28%) | Task 7 (2.80%) | Task 3 (2.80%) |

¹⁴ Equally, one could measure the number of times a given task is affected by all possible failure cascades in order to construct a sensitivity index – a similar approach can be seen in Ellinas, C., Allan, N., Cantle, N., 2015a. How resilient is your organisation? From local failures to systemic risk, ERM Symposium 2015, Washington D.C., USA.

| | | | | | |
|--------|----------------|----------------|----------------|----------------|-----------------|
| Case 4 | Task 1 (5.23%) | Task 2 (4.26%) | Task 8 (3.16%) | Task 6 (2.80%) | Task 3 (2.80%) |
| Case 5 | Task 1 (5.22%) | Task 2 (4.01%) | Task 8 (3.16%) | Task 6 (2.79%) | Task 3 (2.79%) |
| Case 6 | Task 1 (5.22%) | Task 2 (4.01%) | Task 6 (3.28%) | Task 3 (2.79%) | Task 7 (2.67%) |
| Case 7 | Task 1 (5.23%) | Task 6 (3.65%) | Task 2 (3.41%) | Task 7 (2.68%) | Task 9 (2.68%) |
| Case 8 | Task 1 (5.24%) | Task 2 (3.41%) | Task 6 (3.17%) | Task 7 (2.68%) | Task 9 (2.68%) |
| Case 9 | Task 1 (5.07%) | Task 6 (3.62%) | Task 2 (2.78%) | Task 7 (2.66%) | Task 10 (2.42%) |

The shift in task criticality can be visualised in the context of the entire project duration – see Figure 7. Interestingly, in Case 1 the entirety of Top 10 most critical tasks are scheduled for the first half of the project, with their individual duration being relatively small. Conversely, the Top 10 most influential tasks are spread out across the entire duration of the project, while individual durations appear to span from relatively short to long tasks.

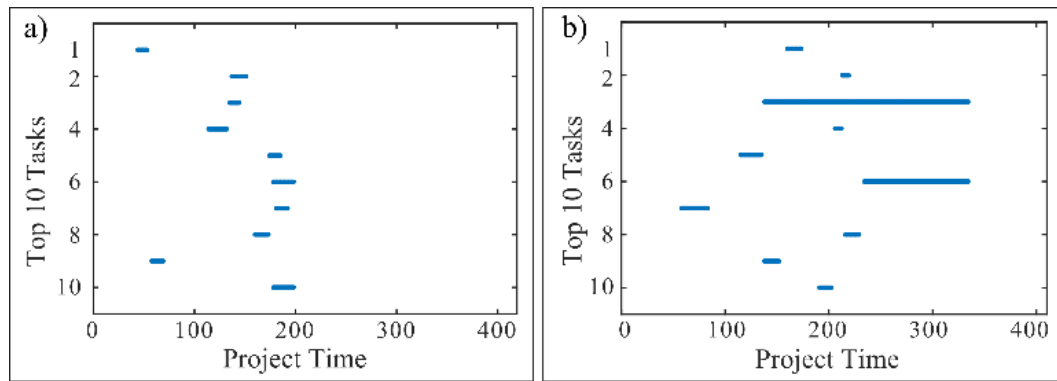


Figure 7: Index of Top 10 tasks (y-axis), in terms of their capacity to trigger large failure cascades, across the overall duration of the project, in days (x-axis). Subplot (a) and (b) correspond to Case 1 and 9 respectively.

4.2. Conflict Management

Having tasks that are both locally and globally important should minimise friction between (sub) project stakeholders. Yet, this is not the case for this specific example, where the dichotomy between the two is highlighted by the low correlation between the two – see Table III.

Table III: Typical Pearson Correlation Coefficients between global and local task importance. Results correspond to Case 1, and are representative of the entire dataset. All noted values are statistically significant ($p < 0.01$).

| Case | | \widehat{LI}^{100} | | |
|------------|------------|----------------------|--------|--------|
| | | w=0 | w=20 | w=40 |
| GI^{100} | $\sigma=1$ | 0.3936 | 0.5201 | 0.6402 |
| | $\sigma=2$ | 0.2961 | 0.4318 | 0.3119 |
| | $\sigma=3$ | 0.4513 | 0.2826 | 0.3937 |
| | $\sigma=4$ | 0.3661 | 0.3342 | 0.3527 |

Focusing on the local importance of the tasks, variance and the mixing pattern that describe the (sub) contractor activity within a project can substantially affect the local importance of tasks. With respect to the impact of the number of involved contractors, consider the cumulative probability distribution of local task importance as seen in Figure 8. The effect of an increasingly high number of involved (sub) contractors is reflected by a continuous increase in the probability of encountering tasks with any given value. For example, in the case of $\sigma = 1$ (low number of involved (sub) contractors), the probability of encountering a task with a local importance of at least 0.1% is 0.11; in the case of $\sigma = 4$ (high number of involved (sub) contractors) this probability increases to 0.25. As expected, the case of increased variance also results to a higher maximum value of local importance ($\max \widehat{LI}^\alpha$) with values of 3.32 and 6.44 in the case of $\sigma = 1$ and $\sigma = 4$ respectively.

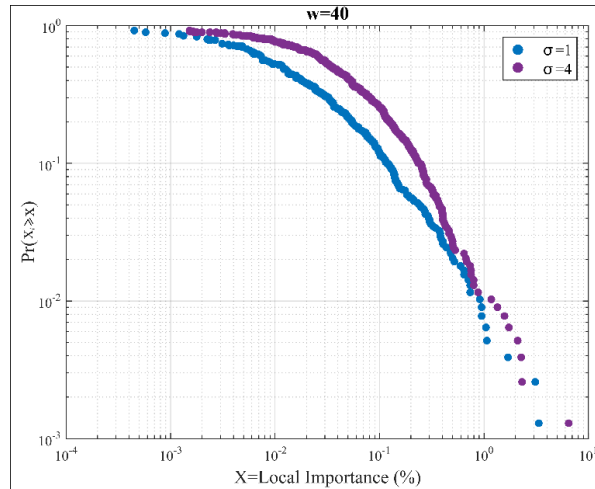


Figure 8: Cumulative probability distribution of local importance of tasks under the case of low ($\sigma = 1$; blue) and high ($\sigma = 4$; purple) variance in terms of the number of (sub) contractors involved under the case of highly clustered activity ($w = 40$).

Figure 9 examines the combined effect of both variance and mixing pattern by presenting two distinct scenarios: low variance (Figure 9a) and high variance (Figure 9b). In the first scenario, the mixing pattern (w) has little impact to the local importance of the each task, with both plots being relatively close to each other – see Figure 9a.

This is not the case for the second scenario (Figure 9b), where the combination of increased variance ($\sigma \gg$) and clustering ($w \gg$) significantly affects the probability of locally important tasks to emerge. Specifically, the increasingly clustered scenario ($w=40$) leads to the emergence of increasingly important task, when X is limited up to roughly 3%. In other words, the probability of encountering tasks that can affect up to 3% of all tasks performed by a given (sub) contractor is enhanced when the activity of a (sub) contractor is clustered.

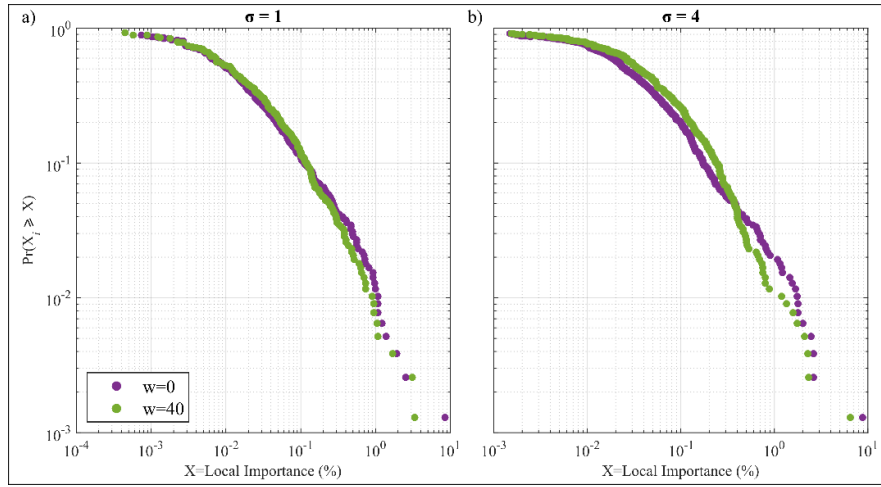


Figure 9: Cumulative probability distribution of local importance of tasks, under two distinct cases – (a) low and (b) high variance. As such, each subplot presents results for both well-mixed (purple) and clustered (green) activity. In the case of high variance (subplot (b)) a qualitatively different behaviour is triggered by the mixing activity; this is not the case for subplot (a).

As the considered impact increased past the 3% mark, the well-mixed scenario overcomes the clustered scenario, resulting to an increased probability of locally important tasks to emerge. In other words, the probability of encountering tasks that can affect more than 3% of all tasks performed by any given (sub) contractor is enhanced as the activity of a (sub) contractor becomes increasingly spread across the entire project.

5. Discussion

The aim of this work is to illustrate the capacity of a recently introduced model (see (Ellinas et al., 2015b)) in tackling a number of important challenges in the context of PM. Specifically, two examples are presented: (a) temporal monitoring of a project and (b) the emergence of locally important tasks. An interpretation of the results is subsequently provided, with an emphasis on the utility of the adopted framework.

5.1. Project Temporal Monitoring

Monitoring the state of a project as a challenging yet vital task for the project risk management function. Part of the challenge lies in the dynamic nature of projects, evident by the shifting topology of the activity network (i.e. nodes and/or links added/removed – see Table I) used to capture the state of a construction project during various stages. Driven by this changing topology, the susceptibility of the respective activity network to project systemic risk also varies, with the effects being evident at both the macro and micro level.

Focusing on the macro level, Figure 5 and Figure 6 translate these shifts of the activity network topology into (a) the susceptibility of a project to sustain failure cascades, and (b) its sensitivity to changing resources respectively. Results of the analysis strengthen the intuitive notion of a project becoming more robust as it nears its completion. However, this result is not grounded on the normative rationale of simply having less things that can go wrong (due to the decrease in the number of outstanding tasks)– indeed all tasks were included in the analysis of each Case, regardless of whether the specific tasks had been completed. In other words, the increase in the robustness of the activity network, as noted in Figure 5 and 6 (and Table I SI) is not driven by having less tasks that can go wrong. An alternative explanation could perhaps be introduced, where improved understanding of the project by the team (due to a decrease of project uncertainty as the project progresses) leads to an improved depiction of the task interdependences, which consequently leads to an increasingly robust project. In this context, improved robustness would suggest that the involved team is actively improving its knowledge. Uncovering the precise cause of this improvement would require a thorough examination of aspects that can directly influence the topology of these activity networks, which in turn fuel the observed changes in project robustness. Examples of such aspects include changes in supply chain, organisational structure, contractual obligations etc. A systematic examination of these changes goes beyond the purpose of this work, which solely focuses on project schedules, and hence will not be explored further.

Shifting focus to the micro level, Table II captures a well-known challenge of traditional project risk management – the variability of task criticality as the project evolves. Interestingly, the proposed framework is able to capture a number of non-trivial aspects: (a) the most critical task remains constant

throughout all nine time-shots, yet its impact monotonically decreases (an aspect closely linked with the overall improvement mentioned in the previous paragraph); (b) the identify of several critical tasks fluctuates, along with their capacity to affect the project, and (c) the project time period in which critical tasks are scheduled varies – see Table II and Figure 7 respectively.

5.2. Conflict Management

Despite the clear utility of identifying tasks capable of triggering large failure cascades (i.e. leading to the emergence of tasks of high global importance), the procurement process will eventually result to tasks which are of varying interest to the involved (sub) contractor, as each (sub) contractor is assumed to act in its own self-interest (i.e. leading to the emergence of tasks of high local importance). Increased overlap between global and local importance across all tasks should provide the conditions for reduced conflicts. Alas this is not the case, with Table III indicating low levels of correlation between the two (global and local task importance). As such, the cascade mode is used to explore the role of task division to (sub) contractors in order to uncover the effect of its composing aspects.

The activity of such (sub) contractors can be understood in terms of their variance and activity pattern (Figure 1) – these aspects are simulated by varying parameter σ and w respectively. By doing so, two distinct observations can be made: (a) increased variance increases both the probability of observing a task with a given local importance, and the maximum observable local importance value (see Figure 8), and (b) activity pattern acts as the differentiating factor by which two regimes of increasingly frequent, yet moderately important tasks and less-frequent but increasingly important tasks emerge (see Figure 9b). Importantly, for (b) to be observed, increased variance is a necessary condition, evident by the qualitatively different behaviour observed in Figure 9a and b.

In the case of increased variance (Figure 9b), two distinct regimes are observed, separated by the amount of local importance that any given task can possess. Specifically, an increasingly clustered (sub) contractor activity leads to an increase in the emergence of moderately important tasks, with well-mixed activity contributing more to the emergence of higher, locally important tasks. The emergence of the first regime can be understood by considering the two aspects that define local importance – the time between two tasks (eq. 7, first term) and the number of tasks affected (eq. 7, second term). In the case of increasingly large sequences of consecutive tasks (the result of $w \gg 1$), the probability of affecting a large number of nodes is high but the overall time in which the (sub) contractor is occupied in the project is low. However, in the case of a well-mixed scenario, it is less likely for a single node to affect a large number of node, but the probability of having a (sub) contractor involved in the project for an increasingly high amount of time is high – as aspect increasingly important which eventually drives the crossover behaviour and the emergence of two regimes, as noted in Figure 9b.

In other words, it is not the sheer number of involved (sub) contractors that impacts the emergence of locally important tasks but rather the timing in which the involvement of these contractors is scheduled across the project. In the context of conflict management, such insight suggests that traditional procurement methods can be increasingly dangerous in the context of project systemic risk, as an increased number of (sub) contractors provides the necessary conditions in which the activity mixing pattern can lead to either an increase in the emergence of moderately important tasks (when activity is increasingly clustered) or to an increased in the emergence of highly important tasks (when activity is increasingly spread across the entire project).

With respect to the generalizability of this insight, Figure 10 presents a simple example which hints possible limitations. Specifically, consider the two sub-networks used in Figure 10a (2-node chain; 3-node chain), and the consecutive possible combinations that may arise in terms of task ownership. With σ being kept constant across the two (i.e. two contractors involved), the number of possible combinations, in terms of task ownership significantly varies as the network increases in size. As such, consider the case where two distinct activity networks are composed of different portions of these sub-networks (Figure 10b). In this case, the impact of σ and w will influence the emergence of locally important tasks in a distinctly different way, precisely due to this difference in network topology.

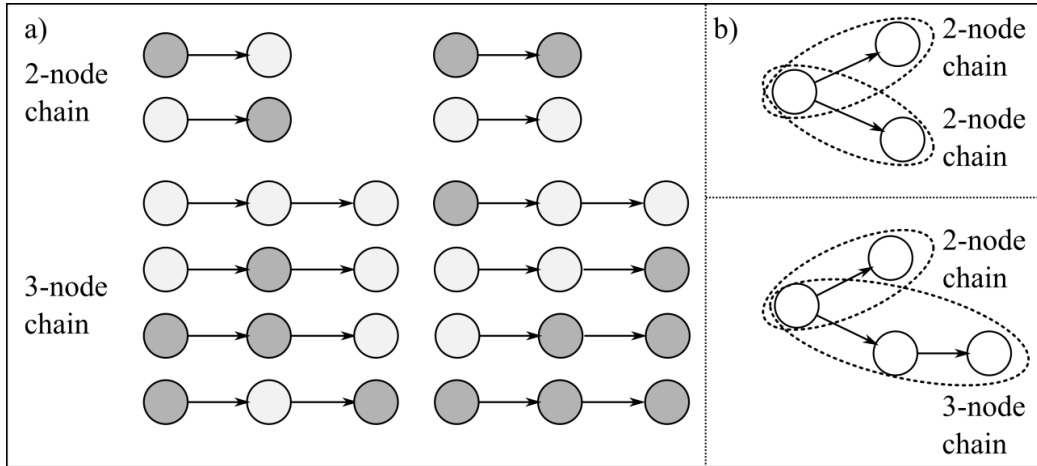


Figure 10: (a) Visual example of how task ownership varies as network topology changes. Colour corresponds to different (sub) contractors; (b) toy activity network composed of different portions of the sub-networks presented in (a). As such, the impact of varying σ and w is bound to vary between the two toy networks.

In the context of this study, this observation translates as follows: the larger the difference between the topology of any given activity network with the one examined herein, the more likely it is that the variance in the number of (sub) contractors and activity pattern will impact the emergence of locally

important task in a different manner. That being said, recent work has illustrated consistent similarities across project activity networks (Ellinas et al., 2014, In Press) despite their seemingly-distinct character. Such commonalities hint at a possible limit in the variability of results that one could resonantly expect across various projects (also see Section 5.3).

5.3. Limitations and Further Work

For the sake of model simplicity and tractability, a number of assumptions have been made that need be acknowledged. For example, it has been assumed that the number of (sub) contractors involved in a project decays exponentially – though this may sound like a reasonable assumption, the range of all possible projects that may take place is immense, and hence instances that challenge this assumption are bound to emerge. It is further assumed that every task is the product of the endeavours of a single (sub) contractor – however in reality, tasks can be jointly delivered by a number of (sub) contractors. Nonetheless, these assumptions are linked with the (sub) contractor assignment process (as described in Section III, C) and hence, can be easily lifted during the operational stage where information around task / (sub) contractor assignment is bound to be known.

Though this work has focused at the operational stage of a project, the techniques introduced (including the cascade model) can be applied at earlier stages to assess project viability. For example, such analysis can be applied during the bidding process, the latter being one of the most cited causes of project failure across a range of domains (Bagies and Fortune, 2006; Frame, 2002; Pearce, 2003). By doing so, the feasibility of a proposed project can be assessed, both in the context of project systemic risk and based on its capacity to fuel conflict between the (sub) contractors involved (i.e. if a project required an increased number of (sub) contractors undertaking of clustered activity, there is a high probability of conflict to arise due to the increased probability of task with high local importance to emerge). Taking it further, the proposed framework could be applied at a higher level of aggregation (i.e. portfolio management), supporting decision making at a strategic level.

Finally, we note that the contribution of this work results from using a theoretical model in tackling two real-world challenges (temporal monitoring of project systemic risk; conflict management), by considering a representative project example. It is reasonable to expect some generalizability of the insights presented herein (e.g. the influence of the number of (sub) contractors involved and their activity pattern in terms of locally important tasks) across various projects due to the presence of topological similarities across project activity networks (Ellinas et al., 2014, In Press). Nonetheless, we encourage a case-by-case analysis in order to capture the unique features of specific projects. Construction of heuristics may be possible through future work by examining a larger pool of projects and deducing the degree upon which the presented insight can be generalised.

6. Conclusion

Project complexity is becoming increasingly recognized as an independent variable that challenges a number of assumptions that underlie traditional management tools and techniques (Geraldi et al., 2011). At the same time, NS has developed rigorous theories that quantify the impact of such complexity across a wide range of complex systems (Barabási, 2007). Despite the fact that project can indeed be considered as complex systems, very little knowledge exchange has taken place between these two domains, perhaps due to the differing nature of the challenges that they aim to tackle. Yet, as project complexity is expected to increase in the following years (Williams, 2002), novel methodologies to tackle the resulting practical challenges are in great demand (PMI, 2013), with NS being in a pristine position to offer a fresh perspective on persistent challenges.

Work by Ellinas et al. (2015b) is such an example, where a theoretical model has been proposed to better understand project systemic risk. Despite its practical orientation (e.g. data requirements being tailored to readily-captured data) the lack of any practical examples can diminish its appeal and perceived relevance to the more practically oriented community of PM. In response, this work adopts the proposed model and tests its practical utility under two challenges – temporal monitoring of project systemic risk and conflict management.

For the first example (temporal monitoring of project systemic risk), we illustrate how the cascade model can be used to identify shifts in the susceptibility of a project to systemic risk as revised activity networks capture changes in the scheduled tasks. At the macro level, it is shown that as the project progresses, their underlying activity network show negligible improvements to small failure cascades, with larger improvements to increasingly large failures. At the micro level, the cascade model is used to identify tasks capable of triggering large failure cascades- importantly the identity of these tasks fluctuates emphasizing the dynamic nature of the project and the need for repeating the analysis as up-to-date schedules surface. Insight of this sort can be used to support the risk management function of a project whilst using already captured data. For the second application example (conflict), it is shown that there is a lack of correlation between globally (of interest to the owner and/or general contractor) and locally (of interest to a given (sub) contractor) important tasks, making the project prone to conflict. Further delving into the influence of (sub) contractor activity, it is shown that both variance and their activity pattern can substantially affect the emergence of locally important task. Insight of this sort can be used to support the formulation of the procurement strategy in order to minimize the likelihood of conflicts to emerge.

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Appendix

1. Definition of quality function

The quality of completion for node i (q_i) is defined as follows:

$$q^{\text{sigm}}(\hat{T}_i) = \frac{1}{1 + \exp(-\gamma\hat{T}_i + \beta)}, \text{ where } \beta = -\ln\left(\frac{1}{q(1)} - 1\right) \text{ and } \gamma = 2\beta \quad (\text{eq.1SI})$$

where \hat{T}_i is the ratio between the actual and planned resource assigned to deliver node i i.e. $\hat{T}_i = \frac{T_i^{\text{actual}}}{T_i^{\text{plan}}}$, where $T_i^{\text{actual}} = T_i^{\text{plan}} + \beta_i^{\text{pdf}}$. Both T_i^{plan} and β_i^{pdf} are measured in work days.

2. Formal definition of spreading power and sensitivity

The spreading power for node i is defined by eq. 2SI

$$\mathcal{C}_i^{\text{SP}} = \left(\sum_{\substack{i=1 \\ i \neq j}}^{n-1} \sum_{k=1}^{n-1} \frac{\mathbf{A}^k(i, j)}{k} \right) \times \left(\frac{T_i^{\text{end}} - T_i^{\text{start}}}{T_N^{\text{end}} - T_1^{\text{start}}} \right) \quad (\text{eq.2SI})$$

where the first term corresponds the number of paths at which node i can reach j , weighted over the length of each path (i.e. number of links traversed) k . The second terms corresponds to a ratio between the duration of task i against the overall project duration.

Similarly, the sensitivity of node j is defined by eq. 3SI.

$$\mathcal{C}_j^{\text{S}} = k_j^{\text{in}} \times \left(\frac{T_N^{\text{end}} - T_1^{\text{start}}}{T_j^{\text{end}} - T_j^{\text{start}}} \right) \times \left(\frac{T_N^{\text{end}} - T_1^{\text{start}}}{\max \left(1, \frac{1}{k_j^{\text{in}}} \sum_{i \in I} (T_i^{\text{end}} - T_j^{\text{start}}) \right)} \right) \quad (\text{eq.3SI})$$

where $k_j^{\text{in}} = \sum_{i=1}^n \mathbf{A}(i, j)$, I is the set of nodes that directly connects to j i.e. $\mathbf{A}(i, j) = 1$ and the max function ensures that $\mathcal{C}_j^{\text{S(slack)}}$ is always defined (and in effect, remains unitless). The first term effectively captured the number of predecessors (i.e. number of incoming connections) to node j . The second term introduces the inverse ratio between the overall project duration and the duration of node j , with the third term taking into account the slack time between node i and j .

Finally, note that both $\mathcal{C}_i^{\text{SP}}$ and \mathcal{C}_j^{S} are normalized as follows according to eq.4SI and eq. 5SI:

$$\hat{\mathcal{C}}_i^{\text{SP}} = \frac{\mathcal{C}_i^{\text{SP}} - \min \mathcal{C}^{\text{SP}}}{\max \mathcal{C}^{\text{SP}} - \min \mathcal{C}^{\text{SP}}} \text{ where } \hat{\mathcal{C}}_i^{\text{SP}} \in [0,1] \quad (\text{eq.4SI})$$

$$\hat{\mathcal{C}}_j^{\text{S}} = \frac{\mathcal{C}_j^{\text{S}} - \min \mathcal{C}_j^{\text{S}}}{\max \mathcal{C}_j^{\text{S}} - \min \mathcal{C}_j^{\text{S}}} \text{ where } \hat{\mathcal{C}}_j^{\text{S}} \in [0,1] \quad (\text{eq.5SI})$$

3. Descriptive statistics of failure cascade sizes for each Case

Table I SI: Global Statistics for cascade sizes sustained by all Cases ($a = 100$).

| Case | Mean Failure Cascade Size (%) | Standard Deviation | Maximum z-score |
|-------------|--|---------------------------|------------------------|
| Case 1 | 1.813 | 28.246 | 4.744 |
| Case 2 | 2.002 | 33.687 | 5.165 |
| Case 3 | 1.986 | 35.523 | 5.152 |
| Case 4 | 1.990 | 35.541 | 5.149 |
| Case 5 | 1.980 | 35.518 | 5.152 |
| Case 6 | 1.980 | 35.518 | 5.152 |
| Case 7 | 1.802 | 30.960 | 4.393 |
| Case 8 | 2.088 | 38.834 | 5.536 |
| Case 9 | 1.667 | 27.917 | 4.549 |